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High Energy Neutrino Physics*

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THEORETICAL INTERPRETATION OF NEUTRINO EXPERIMENTS

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I. INTRODUCTION

In the last year new experimental results with neutrino beams have been obtained in several laboratories and their theoretical interpretation is the subject of this article. Experiments with neutrino beams are capable of investigating the structure of hadrons and the nature of weak interactions. The first part of this article deals with deep inelastic scattering. It is shown that the scaling phenomenon for the weak structure functions implies the linear rise of the total cross sections and provides bounds for the ratio $\sigma(\bar{\nu} N \to \mu^+ x)/\sigma(\nu N \to \mu^- x)$. Recent determinations of this ratio indicate that it is near the lowest bound allowed by scaling, which, in turn, has several consequences. A comparison of such detailed information with theoretical expectations reveals remarkable consistency between theory and experiment.

The second part deals with neutral currents. Experimental search for neutral currents over the last year established not only new bounds for several processes, but also credible candidates for some of the reactions. A survey of existing results is presented within the context of gauge models of leptonic and semileptonic interactions.

II. TOTAL CROSS SECTIONS

The processes that we are dealing with are shown schematically in Fig. 1. The process is described in the laboratory frame. An incident neutrino with energy E hits a nucleon at rest, leading to a final muon with energy E' and a final hadronic state with momentum P_n. When we sum over all final hadronic states, the process depends on three kinematic variables:

E : incident energy

$\nu = E - E'$: energy transfer

$q^2 = -Q^2 = -4EE'\sin^2\theta/2$: square of the momentum transfer.

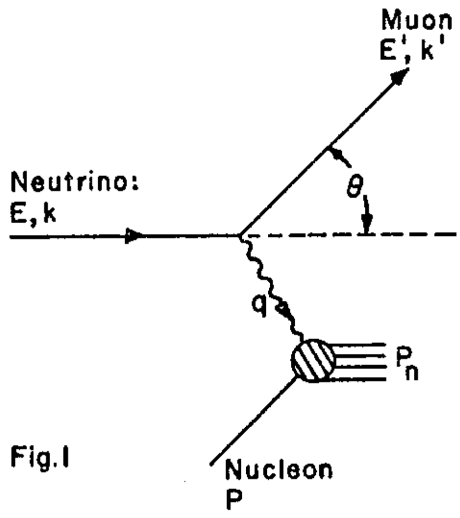

Fig. 1

The explicit functional form of the leptonic vertex is known from the effective current-current interaction Lagrangian. The wavy line indicates an exchange force, and may or may not correspond to a W-boson. For the remaining of this article we do not assume the exchange of an intermediate vector boson, unless otherwise stated. All the interesting structure is hidden in the hadronic vertex.

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The hadronic vertex describes the absorption of a current by a hadron. Since in the experiments the targets are unpolarized, there is no dependence on the spin of the target. The current, however, is a superposition of helicity states. For a space-like current there are three polarization states. The unknown structure functions for the hadronic vertex can be chosen as three total cross sections, corresponding to the absorption of a right-handed, left-handed and scalar current, denoted respectively by

$$\sigma_R(Q^2,\nu),\quad \sigma_L(Q^2,\nu) \text{ and } \sigma_S(Q^2,\nu) \tag{2-1}$$

The double differential cross section[1-3] for incident neutrinos is

$$\frac{d\sigma^{\nu}}{dQ^2 dE'} = \frac{G^2}{2\pi}\frac{E'}{E}\, W_2(Q^2,\nu)\{1+\frac{\nu}{E'}(L)-\frac{\nu}{E}(R)\} \tag{2-2}$$

where

$$\binom{L}{R} = \frac{\begin{pmatrix}\sigma_L\\ \sigma_R\end{pmatrix}}{2\sigma_S+\sigma_L+\sigma_R} \text{ and } F_2(x) = \frac{1}{2\pi}\, Q^2\, \frac{(1-Q^2/2M\nu)}{(1+Q^2/\nu^2)}(2\sigma_S+\sigma_L+\sigma_R) \tag{2-3}$$

The corresponding formula for antineutrinos is

$$\frac{d\sigma^{\bar\nu}}{dQ^2 dE'} = \frac{G^2}{2\pi}\frac{E'}{E}\,\overline{W_2(Q^2,\nu)}\left\{1+\frac{\nu}{E'}(\bar R)-\frac{\nu}{E}(\bar L)\right\} \tag{2-4}$$

The bar over the structure functions indicates that in general they are different from those in Eq. (2-2).

A crucial assumption for the remaining of this discussion is Bjorken's scaling phenomenon.[4] From Eqs. (2-2) and (2-3) we observe that $\nu W_2(Q^2,\nu)$, (R) and (L) are dimensionless quantities. Consequently in the limit

$$Q^2 \to \infty \text{ with } Q^2/2M\nu = \text{finite} \tag{2-5}$$

these functions can oscillate or approach zero, infinity, or a non-trivial function of the dimensionless ratio $x = Q^2/2M\nu$. A few years ago Bjorken remarkably predicted[4] that in the above limit the structure functions approach non-trivial functions of a single dimensionless variable

$$\begin{aligned} \nu W_2(Q^2,\nu) &\to F_2(x)\\ \binom{R}{L} &\to f_{R,L}(x) \end{aligned} \tag{2-6}$$

The scaling phenomenon has been observed for limited ranges of Q^2 and ν in the electroproduction experiments of the SLAC-MIT group.[5] The pleasant surprise is that the structure functions approach this limit rather fast. It settles in for values of $Q^2 \geq 2(\mathrm{GeV}/c)^2$. Such tests will be extended to larger ranges of Q^2 and ν in the NAL experiments.[6] At this time there is no direct test of scaling in neutrino induced reactions. It has been shown, however, that the conventional theory of weak interactions together with the scaling hypothesis lead to numerous consequences whose verification provide indirect tests of scaling. We discuss these consequences in this and the following section.

Theorem: 1) If all three structure functions scale[4] then

$$\sigma^{\nu} \underset{E\to\infty}{\to} CE_{\nu}$$
$$\sigma^{\bar{\nu}} \underset{E\to\infty}{\to} C'E_{\bar{\nu}} \tag{2-7}$$

2) For targets[3] with equal numbers of protons and neutrons (isoscalar) the scaling of all three structure functions implies

$$1/3 \leq \sigma^{\bar{\nu}}/\sigma^{\nu} \leq 3 \tag{2-8}$$

Proof: (i) Integrating over Q^2 and appealing to scaling

$$\frac{d\sigma}{dE'} = \frac{G^2}{2\pi}\frac{E'}{E} 2M\left\{\int F_2(x)\frac{dQ^2}{2M\nu}\right\}\left\{1 + \frac{\nu}{E'}\langle L\rangle - \frac{\nu}{E}\langle R\rangle\right\} \tag{2-9}$$

where

$$0 \leq \langle L,R\rangle \equiv \frac{F_2(x)\,(L,R)\,dx}{F_2(x)\,dx} \leq 1 \tag{2-10}$$

Thus scaling decouples the integrations of x and E', so that the dependence in E' is explicitly exhibited. Integrating over E'

$$\sigma^{\nu} = \frac{G^2}{2\pi} 2ME\left\{\int F_2(x)\,dx\right\}\left\{\frac{1}{2} + \frac{1}{2}\langle L\rangle - 1/6\langle R\rangle\right\} \tag{2-11}$$

Similarly for antineutrinos.

(ii) For isoscalar targets

$$F_2(x) = \bar{F}_2(x),\ \langle \bar{L},\bar{R}\rangle = \langle L,R\rangle \tag{2-12}$$

by charge symmetry. Therefore

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{\frac{1}{2} + \frac{1}{2}\langle R\rangle - 1/6\langle L\rangle}{\frac{1}{2} + \frac{1}{2}\langle L\rangle - 1/6\langle R\rangle}. \tag{2-13}$$

where $0 \leq \langle L\rangle \leq 1$, $0 \leq \langle R\rangle \leq 1$ and $\langle 2S\rangle + \langle L\rangle + \langle R\rangle = 1$. Equation (2-8) now follows with the lower limit corresponding to $\langle L\rangle = 1$ and $\langle R\rangle = 0$.

Figure (2) shows the measurements from the Gargamelle collaboration.[7] The cross sections are consistent with a linear rise. The statistics are too limited to provide undisputed evidence in favor of the linear rise. Consequently tests of other consequences of scaling are desirable. Figure (3) shows the ratio of the cross sections. If we assume that the total cross sections rise linearly with energy starting at 2 GeV, then their ratio is determined with good accuracy:

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}}/\,\mathrm{exp} = 0.38 \pm 0.02 \tag{2-14}$$

It is close to the lowest bound allowed by scaling. Preliminary results at higher energies from NAL[8] are also consistent with the interpretation that the ratio of the total cross sections is in the neighborhood of 1/3. Figure 4 shows the NAL point.

The simplicity of the theorem is not indicative of the stringent constraints that it implies, because semileptonic interactions are not restricted by the bounds which are valid in hadronic interactions. For instance, Froissart's theorem[9] requires that hadronic total cross sections can grow at most like $(\ell nE)^2$. This theorem, however has no implications for semileptonic reactions because two of the basic assumptions required in the proof the theorem do not hold for semileptonic reactions. Namely, Froissart's theorem is based on

(i) absence of zero mass particles

(ii) quadratic unitarity

both of which are absent in semileptonic reactions, because we do have zero mass particles and unitarity is linear.

In addition, the Pomeranchuck theorem[10] refers to the hadronic part of the diagram and the ratio $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$ can be different from unity at very high energies.

III. FLUX INDEPENDENT MOMENTS AND THEIR SIGNIFICANCE

In analyzing neutrino experiments one is faced with several intrinsic problems: (i) difficulties in determining the neutrino flux, (ii) uncertainties in determining the initial energy and (iii) limited statistics for specific regions of phase space. It is of interest, therefore, to ask whether it is possible to reformulate consequences of fundamental principles (locality, charge symmetry, scaling, ...) in terms of quantities which are flux and perhaps energy independent. To achieve this objective we can define mean values of the form

$$\langle f(Q^2, E_\mu)\rangle \equiv \frac{1}{\sigma_{tot}} \int f(Q^2, E_\mu)\, \frac{d}{dQ^2 dE_\mu}\, dQ^2 dE_\mu \tag{3-1}$$

where $f(Q^2, E_\mu)$ can be chosen to be E'/E, $Q^2/2ME = \frac{2E'}{M}\sin^2\frac{\theta}{2}$, ... Such mean values are useful even with limited statistics since they average over regions of phase space. They are obviously flux independent. In addition, by invoking the scaling hypothesis and utilizing available data we shall show that at high energies they approach constant limits which are accurately determined.

We examine first the mean energy[11] carried by the muon

$$\langle \frac{E'}{E} \rangle = \frac{1}{\sigma_{tot}} \int \left(\frac{E'}{E}\right) \frac{d\sigma}{dQ^2 d\nu} dQ^2 d\nu \tag{3-2}$$

The scaling of all three structure functions implies

$$\frac{1}{2} \leq \langle \frac{E'}{E} \rangle_{\nu} \leq \frac{3}{4} \tag{3-3}$$

where the subscript ν refers to neutrinos. This result is obtained readily by following the same line of reasoning as that of the theorem in the previous sections. After integration over Q^2 and E' one obtains

$$\langle \frac{E'}{E} \rangle_{\nu} = \frac{\frac{1}{3} + \frac{1}{6}\langle L \rangle - \frac{1}{12}\langle R \rangle}{\frac{1}{2} + \frac{1}{2}\langle L \rangle - \frac{1}{6}\langle R \rangle} \tag{3-4}$$

where the mean values on the right hand side were defined in (2-10). As a result we find the limits of (3-3), with the upper bound corresponding to $\langle R \rangle = 1$, $\langle L \rangle = 0$ and the lower bound to $\langle R \rangle = 0$, $\langle L \rangle = 1$.

In order to study the sensitivity of such bounds on the underlying assumptions, we can proceed in two different directions. First we relax the scaling hypothesis. Consider the case where only $F_2(x) = \nu W_2$ scales and allow for the possibility that (L) and (R) do not scale. Then

$$\langle \frac{E'}{E} \rangle = \frac{\frac{1}{3} + \frac{1}{6}\langle \tilde{L} \rangle - \frac{1}{12}\langle \tilde{R} \rangle}{\frac{1}{2} + \frac{1}{2}\langle L \rangle - \frac{1}{6}\langle R \rangle} \tag{3-5}$$

where $\langle \tilde{L} \rangle$ and $\langle \tilde{R} \rangle$ are again less than unity but independent of $\langle L \rangle$ and $\langle R \rangle$. The corresponding bounds now are

$$\frac{1}{4} \leq \langle E'/E \rangle \leq 1 \quad \text{(Scaling of } \nu W_2 \text{ only)}\,. \tag{3-6}$$

It is worth emphasizing here the close analogy of the bounds obtained above with the bounds obtained for the ratio of the total cross sections. If all structure functions scale, then the total cross section rises linearly with energy and the ratio of cross sections is a constant. If only νW_2 scales, then the ratio of cross sections is again bounded but it is not required to be a constant.

Proceeding in a different direction we supplement the scaling hypothesis with existing data and try to obtain more restrictive bounds. In view of recent data, it seems reasonable to consider bounds in the case when the ratio of the cross sections is close to 1/3:

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{1}{3}(1 + \epsilon), \quad \epsilon \ll 1. \tag{3-7}$$

Equations (2-13), (3-7) and the trivial identity

$$\langle R\rangle + \langle L\rangle + 2\langle S\rangle = 1 \tag{3-8}$$

imply the constraint equation

$$\frac{\langle R\rangle}{\langle L\rangle} + \frac{3\langle S\rangle}{4\langle L\rangle} = \frac{3}{8}\epsilon + 0(\epsilon^2). \tag{3-9}$$

Maximizing and minimizing (3-4) subject to the constraint equation we obtain [11, 12]

$$\frac{1}{2} + \frac{1}{32}\epsilon \le \langle\frac{E'}{E}\rangle_{\nu} \le \frac{1}{2} + \frac{1}{12}\epsilon \quad . \tag{3-10}$$

Similar arguments can be carried out for antineutrino induced reactions [11, 12]

$$\frac{3}{4} - \frac{9}{32}\epsilon \le \langle\frac{E'}{E}\rangle_{\bar{\nu}} \le \frac{3}{4} - \frac{\epsilon}{8} \ . \tag{3-11}$$

Experimentally the mean values have been determined [13] to be

$$\langle\frac{E'}{E}\rangle_{\nu} = 0.55 \pm 0.10 \quad \text{and} \quad \langle\frac{E'}{E}\rangle_{\bar{\nu}} = 0.69 \pm 0.09$$

in good agreement with the theoretical expectations.

The same analysis has been extended to other quantities. [11, 12, 14] Of particular interest is the mean value

$$\langle\frac{Q^2}{2ME}\rangle_{\nu} \equiv \langle\frac{2E'}{M}\sin^2\frac{\theta}{2}\rangle \equiv \langle z\rangle \equiv \langle xy\rangle \tag{3-13}$$

because it is determined by the energy and angle of the outgoing lepton. It has been known for some time, that scaling implies a linear energy dependence of the mean value of Q^2 at high energies. It also implies the bound

$$0 \le \langle\frac{Q^2}{2ME}\rangle_{\nu,\bar{\nu}} \le \frac{3}{5} \quad . \tag{3-14}$$

Furthermore, combining scaling with the ratio of the total cross sections we again obtain restrictive bounds [11]

$$2\left(1 + \epsilon - \frac{35}{16}\frac{\epsilon}{\langle x\rangle}\right) \le \frac{\langle\frac{Q^2}{2ME}\rangle_{\nu}}{\langle\frac{Q^2}{2ME}\rangle_{\bar{\nu}}} \le 2(1+\epsilon) \text{ provided } \epsilon \ll \langle x\rangle . \tag{3-15}$$

Experimentally the mean values of $\langle Q^2\rangle$ have been determined in the Gargamelle experiment. [7] Figure 5 shows the mean value of $\langle Q^2\rangle$ plotted as a function of the neutrino energy; while Fig. 6 shows the corresponding curve for antineutrinos. The results of linear fits are:

$$\left.\begin{array}{ll} \text{neutrino} & \langle Q^2\rangle = 0.12 \pm 0.03 + (0.23 \pm 0.01)E \\ \text{antineutrino} & \langle Q^2\rangle = 0.09 \pm 0.03 + (0.14 + 0.015)E \end{array}\right\} E > 1 \text{ GeV}$$

neutrino $\langle Q^2 \rangle = (0.22 \pm 0.06) + (0.21 \pm).02)E$

antineutrino $\langle Q^2 \rangle = (0.11 \pm 0.08) + (0.14 \pm 0.03)E$ $\Big\}\, E > 2$ GeV

The agreement with the theoretical expectation (3-15) is again good.

It has been indicated in this section that the scaling hypothesis combined with charge symmetry leads to several predictions, which can be compared with existing experimental data. So far all such comparisons reveal remarkable agreement between theory and experiment. This situation, however, may change at higher energies. De Rújula and Glashow[12] have emphasized that in addition to the conventional Cabibbo current there may exist another component which is isoscalar and changes charm, a conjectured new quantum number conserved by strong and electromagnetic interactions. By universality these two components may have the same coupling constant, but only the Cabibbo current is effective below the threshold for the production of charmed states. Consequently, one expects violations of both charge symmetry and scaling at the threshold of charmed states. In addition one expects modifications of the sum rules.[15]

IV. FURTHER ANALYSIS OF THE DATA

The constraint equation has two further consequences.

1) $$\langle S\rangle/\langle L\rangle \le \frac{1}{2}\epsilon \;(\approx 0.06) \qquad (4.1)$$

in agreement in the Callan-Gross relation[16] and corresponding ratios in electroproduction. For comparison the electroproduction ratios[17] are

$$\frac{\sigma_S}{\sigma_T} = 0.14 \pm 0.10 \quad \text{proton} \qquad (4.2)$$

$$\frac{\sigma_S}{\sigma_T} = 0.15 \pm 0.08 \quad \text{deuteron} \qquad (4.3)$$

2) $$\langle R\rangle/\langle L\rangle \le \delta = (3/8)\epsilon \qquad (4.4)$$

This relation may be useful in testing the parton (light cone) relation

$$W_2(V) = W_2(A) \qquad (4.5)$$

where V and A indicate the contributions arising from the vector and axial currents respectively. It has been shown[11] from kinematic arguments that

$$1-4\delta^{\frac{1}{2}} + 0(\delta) \le \frac{\int F_2(V)\,dx}{\int F_2(A)\,dx} \le 1 + 4\delta^{\frac{1}{2}} + 0(\delta) \qquad (4.6)$$

Present data suggest $\delta \simeq 0.05$, so that the above ratio is consistent with the value of one, but Eq. (4.6) is not very restrictive. An accurate determination of such a ratio is rather difficult. The ratio is important, however, because together with the Conserved Vector

Current hypothesis determines the isovector contribution to electroproduction and consequently the isoscalar part.

3) Under slightly different assumptions we can determine from the data two basic integrals. The slopes of the cross sections determine the integral

$$\int F_2^{\nu N}(x)\, dx \simeq 0.47 \pm 0.07 \tag{4.7}$$

where N denotes the average value per nucleon. The slope of $\langle Q^2 \rangle$ as a function of the incoming energy determines the next moment

$$\int x\, F_2^{\nu N}(x)\, dx \simeq \left\{ \langle Q^2/2ME \rangle_\nu + \frac{\sigma^{\bar\nu}}{\sigma^\nu} \langle Q^2/2ME \rangle_{\bar\nu} \right\} \frac{12}{7} \int F_2^{\nu N}(x)\, dx \tag{4.8}$$

$$\approx 0.12$$

To obtain these two results one needs only the scaling of $F_2(x)$ and the conditions $\frac{\sigma_S}{\sigma_R + \sigma_L} \simeq 0$. $\langle R \rangle / \langle L \rangle \approx 0$ suggested by (4.1) and (4.4).

The above integrals can be compared with corresponding integrals in electroproduction. Such comparisons are made by virtue of the following two properties:

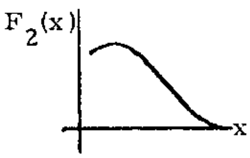
(i) $W_2(V) = W_2(A)$

(ii) The parton (light-cone) suggestion that the isoscalar contribution to $F_2^{\gamma p} + F_2^{\gamma n}$ is less than 10%. It then follows

$$4\left[F_2^{\gamma p} + F_2^{\gamma n} \right] \approx F_2^{\nu p} + F_2^{\nu n} \tag{4.9}$$

where the approximate sign indicates the ambiguity associated with the isoscalar contribution. The relation is expected to hold to within 10-20%. Table (1) summarizes the comparisons between electron and neutrino induced reactions. We finally notice that all such comparisons are in agreement with the predictions of the quark-parton model.

Table 1

Feature	Electrons	Neutrinos
Scaling		$\sigma^\nu \to C \cdot E_\nu$
Spin 1/2	$\sigma_S/\sigma_T = 0.14 \pm 0.10$	$\frac{\langle S \rangle}{\langle L \rangle} \leq \frac{1}{2}\epsilon \approx 0.06$
Momentum carried by Antiparticles	----	$\sigma_R \approx 0 \to \frac{\sigma^{\bar\nu}}{\sigma^\nu} \approx \frac{1}{3}$
$\int F_2(x)\, dx$	0.52 ± 0.08	0.47 ± 0.07
$\int x F_2(x)\, dx$	~ 0.12	~ 0.11

V. NEUTRAL CURRENTS

One of the most pleasant aspects of this field is the many implications that it has for other problems of high energy physics. In 1960 Lee and Yang[18] compiled a list of unresolved problems of weak interactions; shown in Table 2.

Table 2

Questions raised by Lee and Yang [Phys. Rev. Letters 4, 307 (1960)]	Experimental answers from ν experiments
1) $\nu_\mu = \nu_e$?	$\nu_\mu \neq \nu_e$
2) Lepton conservations	See Ref. 20
3) Neutral Currents ?	See text
4) "Locality"(vector nature of weak interactions)	
5) Universality between ν_μ and ν_e, μ and e?	
6) Charge symmetry?	
7) CVC; isotriplet current?	
8) W?	
9) What happens at high energy ($E_\nu \to$ "unitarity limit")?	

In the intervening years, a good deal of research has gone in resolving these problems. The question of the two neutrinos has been answered satisfactorily by the discovery of two neutrinos.[19] Lepton number conservation[20] has been tested to some degree of accuracy. We discuss next the progress made in the past few years with regards to the third question.

The revived interest on neutral currents arose from the possibility of constructing a renormalizable gauge theory of weak (and electromagnetic) interactions.[21] Several models have been proposed which can achieve this goal at the expense of introducing neutral currents. Originally, the theories were concerned with leptonic interactions. Subsequently, they were generalized to account, by virtue of universality, for semi-leptonic reactions. We review here the present experimental status together with the corresponding theoretical predictions.

Leptonic Interactions

Models based on the symmetry group SU(2) × U(1) contain a neutral current operator

$$J^{\ell}_{\mu} = \frac{-ig}{\sin\theta_W} \bar{\psi}_L \gamma_\mu (t_3 - Q\sin^2\theta_W)\psi_L \qquad (5.1)$$

where $Q = t_3 + y$, $e = g\sin\theta_W$, ψ_L a left-handed spinor of a multiplet and $\vec{t}, y$ are the weak isospin and hypercharge, respectively. In models where the left-handed leptons belong to a vector,[22, 23] the neutral current decouples completely from the neutrino. When the left-handed leptons belong to a spinor, neutral currents appear[23] in neutrino induced reactions.

A prototype of the latter case is the Weinberg-Salam model, where the effective part of the Lagrangian pertinent to leptonic reactions is

$$\mathscr{L}_L = \frac{G}{\sqrt{2}} \left\{ \bar{\nu}\gamma_\mu(1+\gamma_5)\nu\, \bar{e}\gamma^\mu(g_V + g_A\gamma_5)e \right\} \qquad (5.2)$$

The effect of the neutral current is to change the values of g_V and g_A from those of the (V-A) theory. For the reactions

$$\nu_\mu e^- \rightarrow \nu_\mu e^- \qquad (5.3)$$

$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^- \qquad (5.4)$$

the differential cross section per unit energy of the recoil electron has the form

$$\frac{d\sigma}{dE'} = \frac{G^2 m}{2\pi} \left[(g_V + g_A)^2 + (g_V - g_A)^2 (1 - \frac{E'}{E})^2 + \frac{mE'}{E^2}(g_A{}^2 - g_V{}^2) \right] \qquad (5.5)$$

where E and E′ are the laboratory energies of the incident neutrino and recoiling electron and m is the electron mass.

Searches for the processes (5.3) and (5.4) were made in the Gargamelle experiment. One "good" candidate for reaction (5.4) was found in the antineutrino film satisfying the selection criteria. The probability that this event is due to non-neutral current background is less than 3%. The same experiment also set new upper limits for the cross sections

$$\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) \leq 0.26 \times 10^{-41}\ E_\nu,\ cm^2 \qquad (5.6)$$

$$\sigma(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-) \leq 0.88 \times 10^{-41}\ E_{\bar{\nu}},\ cm^2 \qquad (5.7)$$

at 90% confidence level. Comparison with the Weinberg-Salam model provides the bounds

$$0.10 \leq \sin^2\theta_W \leq 0.60 \qquad (5.8)$$

In a different experiment Gurr, Reines and Sobel[26] use a $\bar{\nu}_e$ beam from a nuclear reactor and search for the reaction $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$. They observe only a region of the phase space. When their results are translated into total cross sections they imply

$$\frac{\sigma(\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-)/\exp}{\sigma(\nu_e + e^- \rightarrow \nu_e + e^-)/V\text{-}A} \leq 3 \quad \text{(to better than 90\% c.l.)} \qquad (5.9)$$

An analysis[27] of this experiment in terms of the Weinberg-Salam model provides the bound

$$\sin^2\theta_W \le 0.40 \tag{5.10}$$

Semileptonic Interactions:

The term of the effective Lagrangian relevant for semileptonic interactions has the form:

$$\mathscr{L}_{SM} = \frac{G}{\sqrt{2}} \;\bar{\mu}\gamma^\alpha(1+\gamma_5)\nu(J^1_\alpha + iJ^2_\alpha) + \text{h.c.} + \bar{\nu}\gamma^\alpha(1+\gamma_5)\nu J^{(0)}_\alpha \tag{5.11}$$

with the hadronic neutral current given by

$$\begin{aligned} J^{(0)}_\alpha &= J^3_\alpha + yJ^{em}_\alpha + zJ^s_\alpha \\ &= A^3_\alpha + (1+y)\; V^3_\alpha + J'^s_\alpha \end{aligned} \tag{5.12}$$

where J^3_α is the third component of isospin for the usual weak current
J^{em}_α is the electromagentic current and
J^s_α is an isoscalar current

This form of the hadronic current is representative of several models discussed in the literature. Ignoring strange particles altogether, an extension[28] of the Weinberg-Salam model to hadrons is obtained by identifying $\frac{1}{2}(1+\gamma_5)\binom{p}{n}$ as the left-handed nucleon doublet. Then proceeding as in the leptonic case a neutral current is introduced with $z = 0$ and $y = -2\sin^2\theta_W$. Such a model is obviously unrealistic. The usual quark picture with three quarks (p, n, λ) is also unrealistic, because $\Delta s = 1$ neutral currents are unavoidable. A general solution to this problem is to introduce more quarks[28] and avoid the $\Delta s = 1$ neutral currents by adopting the Glashow-Iliopoulos-Maiani scheme.[29] Several models fall into this category[30] with $y = -2\sin^2\theta_W$ and $z \neq 0$. In order to bound the parameter $\sin^2\theta_W$, we appeal to universality and argue that it is the same parameter which occurs in purely leptonic reactions. The bound (5-10) from the Gurr-Reines-Sobel experiment is, at the moment, the most restrictive and will be used in the subsequent numerical estimates.[31]

We now compare the theoretical predictions with the experimental bounds.

Total Cross Sections

Neutral current candidates in the total cross sections have been observed in the CERN experiment.The events behave as if they arise from neutral current processes induced by neutrinos and antineutrinos. When all the Gargamelle[32] events with only hadrons in the final state and no visible muon are attributed to neutral currents they lead to the ratios

$$R \equiv \frac{\sigma(\nu + \text{freon} \to \nu + x_1)}{\sigma(\nu + \text{freon} \to \mu^- + x_2)} = 0.21 \pm 0.03 \tag{5.12}$$

and

$$R \equiv \frac{\sigma(\bar{\nu} + \text{freon} \rightarrow \bar{\nu} + x_3)}{\sigma(\bar{\nu} + \text{freon} \rightarrow \mu^+ + x_4)} = 0.50 \pm 0.09 \qquad (5.14)$$

Within the Weinberg-Salam model the contribution of the neutral currents can be bounded from below. For isoscalar[33, 34] targets

$$R = \frac{[\sigma(\nu+p \rightarrow \nu+X_1) + \sigma(\nu+n \rightarrow \nu+X_2)]}{[\sigma(\nu+p \rightarrow \mu^- + X_3) + \sigma(\nu+n \rightarrow \mu^- + X_4)]} \geq \frac{1}{6}(1+x+x^2) \qquad (5.15)$$

and similarly[34]

$$R = \frac{[\sigma(\bar{\nu}+p \rightarrow \bar{\nu}+X_1) + \sigma(\bar{\nu}+n \rightarrow \bar{\nu}+X_2)]}{[\sigma(\bar{\nu}+p \rightarrow \mu^+ + X_3) + \sigma(\bar{\nu}+n \rightarrow \mu^+ + X_4)]} \geq \frac{1}{2}(1-x+x^2) \qquad (5.16)$$

where $x = 1 - 2\sin^2\theta_W$. The experiments however are not on isoscalar targets, but since most of the contribution to the cross section comes from large values of Q^2 and comparable values of ν it is safe to assume that the process is incoherent. Then defining $R(Z,A)$ in analogy to the R occurring in (5.15), but on a nucleus with Z protons and (A-Z) neutrons we obtain

$$R(Z,A) \geq \frac{Z}{A-Z} R \geq 0.17 \qquad (5.17)$$

The bounds (5.15) and (5.16) should be rather restrictive. When the isoscalar contribution of the neutral current is zero and the V-A interference maximal, (5.15) and (5.16) become equalities. The fact that the V-A interference is almost maximal is confirmed by the ratio of the charged total cross sections. Estimates of the isoscalar contribution improves the bounds, as it is verified by studies[35] of specific models. The bounds from two model calculations are shown in Fig. 7 together with the bounds (5.15) and (5.16). Figure 8 shows the model predictions of $d\sigma/dy$ as a function $y = \frac{\nu}{E_\nu} = \frac{E_{hadrons}}{E_\nu}$.

Single π^0 production

There are two experimental upper bounds for the ratio

$$R_1 = \frac{\sigma(\nu + "p" \rightarrow \nu p \pi^0) + \sigma(\nu "n" \rightarrow \nu n \pi^0)}{2\sigma(\nu "n" \rightarrow p\pi^0\mu^-)} \leq 0.14$$

BNL-Columbia[36]
(W. Lee)

≤ 0.21 (5.18)
Gargamelle[37]

It is important to notice that protons and neutrons in the target are not free but they are bound in nuclei. Consequently charge exchange effects are important[38] and can introduce significant contributions to theoretical estimates of R_1.

There are two types of calculations available at this moment. B. W. Lee [39] calculated a bound in the static model assuming $I = 3/2$ dominance. The bound obtained is considerably larger than the values allowed by experiment. A more recent calculation by Adler[40] incorporates both $I = 3/2$ and $I = 1/2$ contributions. He finds that the $I = 1/2$ contribution does not substantially modify the static model results. This class of calculations is concerned with free protons and neutrons and should be supplemented by corrections arising from charge exchange effects, before a meaningful comparison can be made with experiment.

In a different approach one considers the scattering from an isospin zero nucleus and describes the final states in terms of the isospin of the resulting nucleus and a pion. In this manner all final state interactions are included, except for electromagnetic effects. The resulting formula is

$$R_1 \geq \frac{1}{4}\left[(r-1)^{\frac{1}{2}} - 2\sin^2\theta_w\left(\frac{V^0_{e.m.}}{\sigma(\nu N\to\mu^-\pi^0 x_3)}\right)^{\frac{1}{2}}\right]^2 \qquad (5.19)$$

where

$$r = \frac{\sigma(\nu+N\to\pi^+\mu+x_1) + \sigma(\nu+N\to\mu^- + \pi^- + x_2)}{\sigma(\nu N\to\mu^-\pi^0 x_3)}$$

For numerical estimates one must know the electroproduction of π^0's in nuclei. Data for the electroproduction of π^0's in nuclei is not yeat available and V^0_{em} was estimated making generous allowances for the uncertainties. In addition we need the ratio r. For $2 \leq r \leq 5$ bounds are obtained which vary from 0.07 to 0.44

All other experimental bounds established so far are also consistent with the theoretical expectations of the Weinberg-Salam model. Their status has been reviewed[11] recently and has not changed since that time. Table 3 presents an overview of the present situation. The most striking feature of the table is the proximity of theoretical bounds with the experimental observations. This suggests that new measurements during the next year will supply decisive information.

In summary, high energy neutrino experiments provide an ideal means for probing (i) the structure of hadrons and (ii) the nature of weak interactions. There are numerous experimental measurements in the deep inelastic region, all of which are consistent with the scaling hypothesis and also with the predictions of the quark-parton model. Among the unresolved questions of weak interactions, special attention was paid to that of the existence of neutral currents. A summary of the present situation indicates

Table 3

Comparison between Experimental and Theoretical Bounds for Neutral Current Reactions

Ratio	Experiment (bounds at 90% C. L.)	Theory
$\frac{\sigma(\nu N \to \nu x')}{\sigma(\nu N \to \mu^- x'')}$	0.21 ± 0.03	≥ 0.19
$\frac{\sigma(\bar{\nu} N \to \bar{\nu} x')}{\sigma(\bar{\nu} N \to \mu^+ x'')}$	0.50 ± 0.09	≥ 0.32
$\frac{\sigma(\nu p \to \nu p \pi^0) + \sigma(\nu n \to \nu n \pi^0)}{2\sigma(\nu n \to \mu^- p \pi^0)}$	≤ 0.14 W. Lee ≤ 0.21 Gargamelle	≥ 0.44 to 0.07
$\frac{\sigma(\nu p \to n\pi^+) + \sigma(\nu p \to \nu p \pi^0)}{\sigma(\nu p \to \mu^- \Delta^{++})}$	≤ 0.46 Cundy, et al. ≤ 0.31 ANL	≥ 0.10
$\frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}$	≤ 0.24	$0.15 \leq R \leq 0.25$
$\frac{\sigma(\nu p \to \nu n \pi^+)}{\sigma(\nu p \to \mu^- \Delta^{++})}$	≤ 0.16	≥ 0.03

that experiments to be performed within a year have the capability of either confirming their existence or eliminating a class of theoretical models. Other questions raised in Table 2 also call for close attention. Progress on several of them has been reported[42] during this summer and considerable improvements are expected soon.

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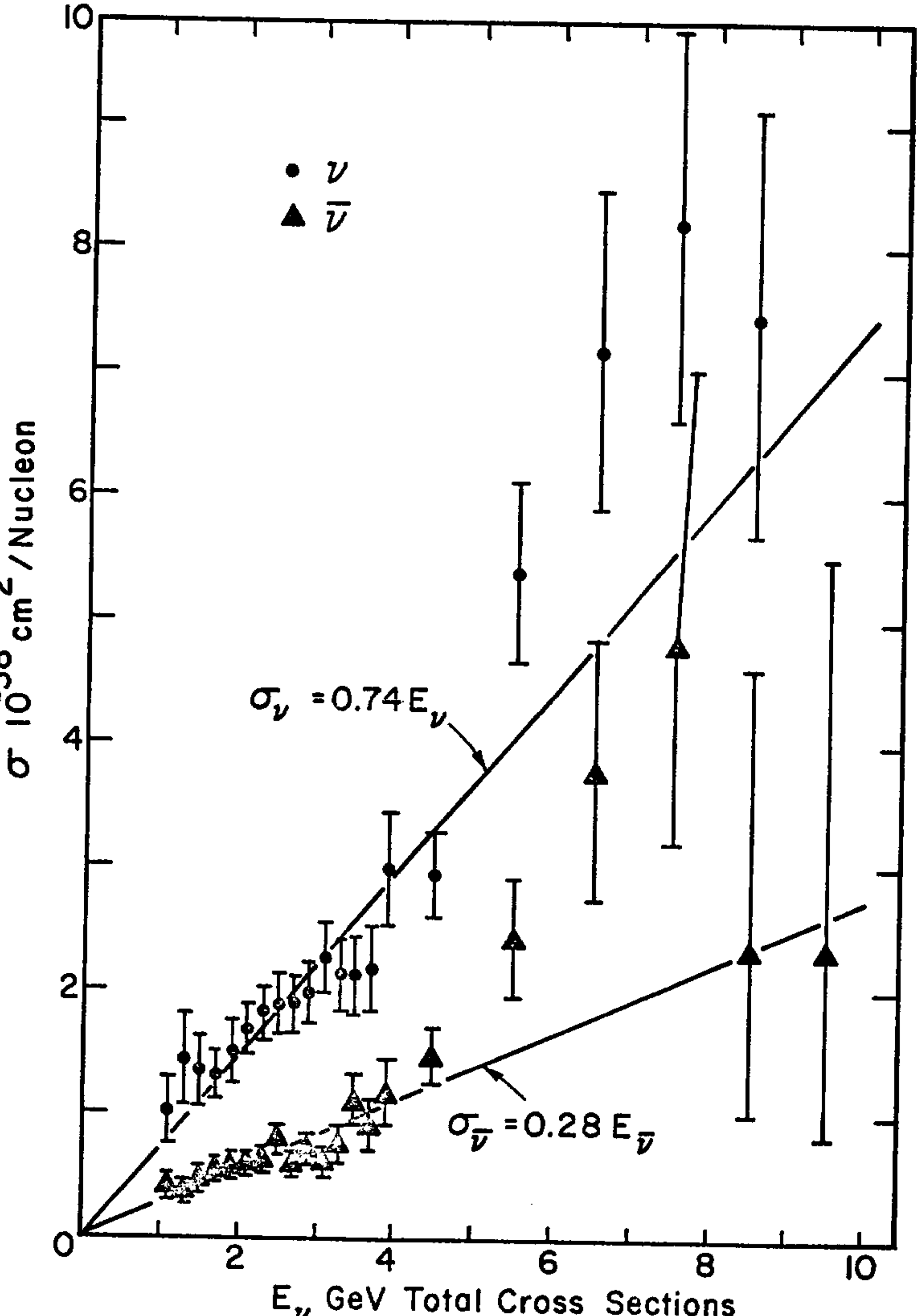

Fig. 2 Neutrino and antineutrino total cross sections as functions of the incident energy (Ref. 7)

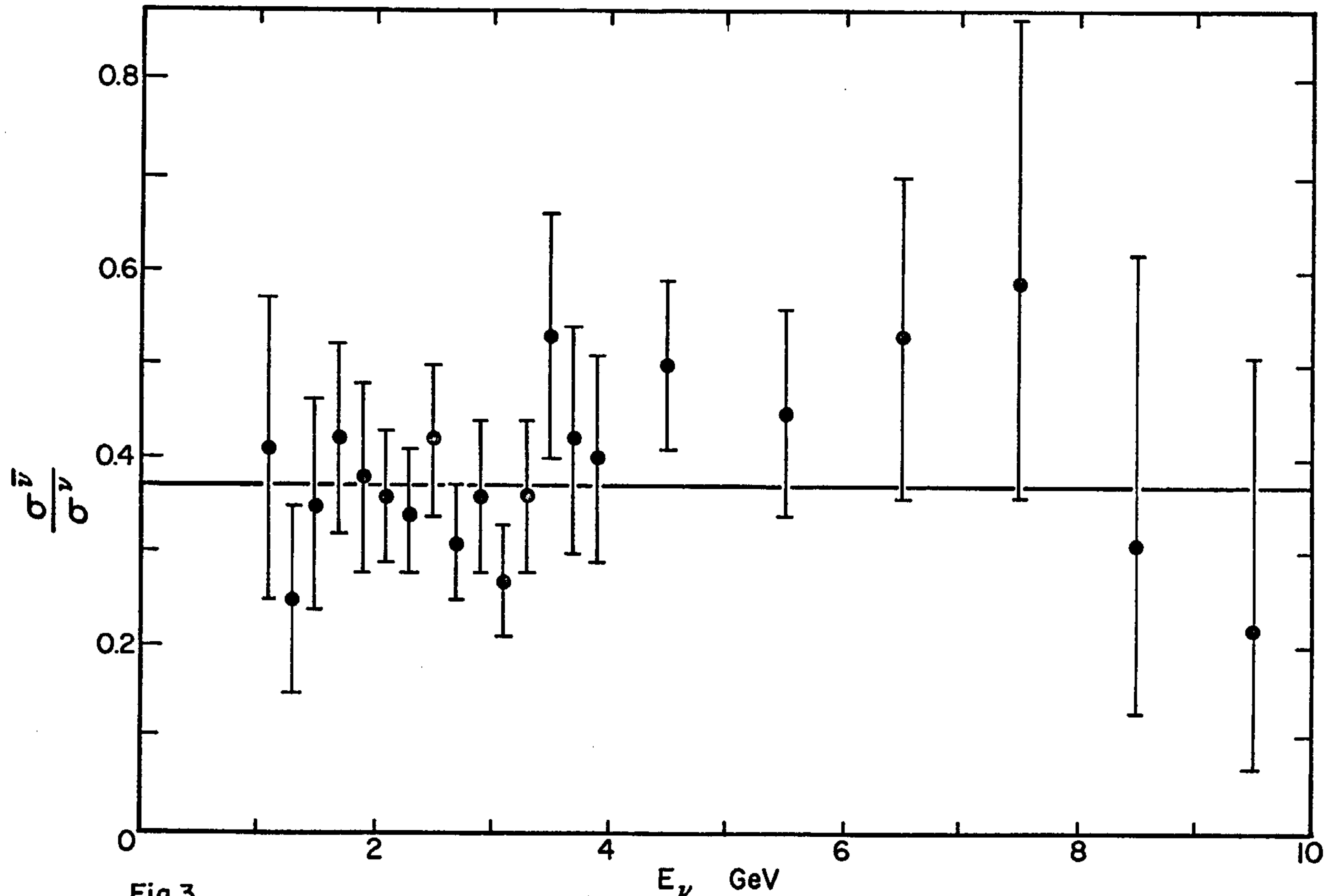

Fig.3
Ratio of the antineutrino to neutrino total cross sections as a function of the incident energy (Ref. 7).

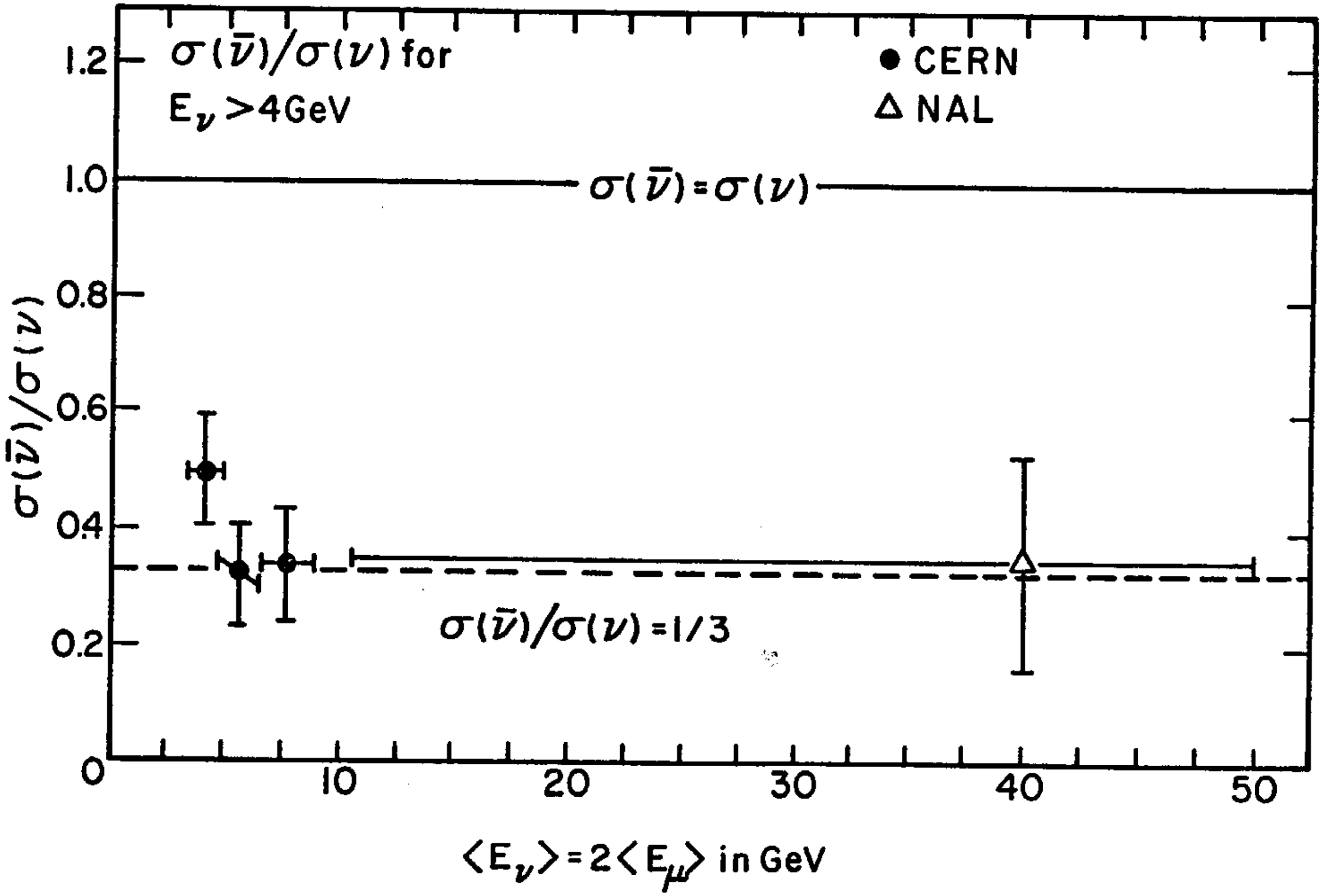

Fig. 4 Ratio of the total cross sections at NAL energies (Ref. 8).

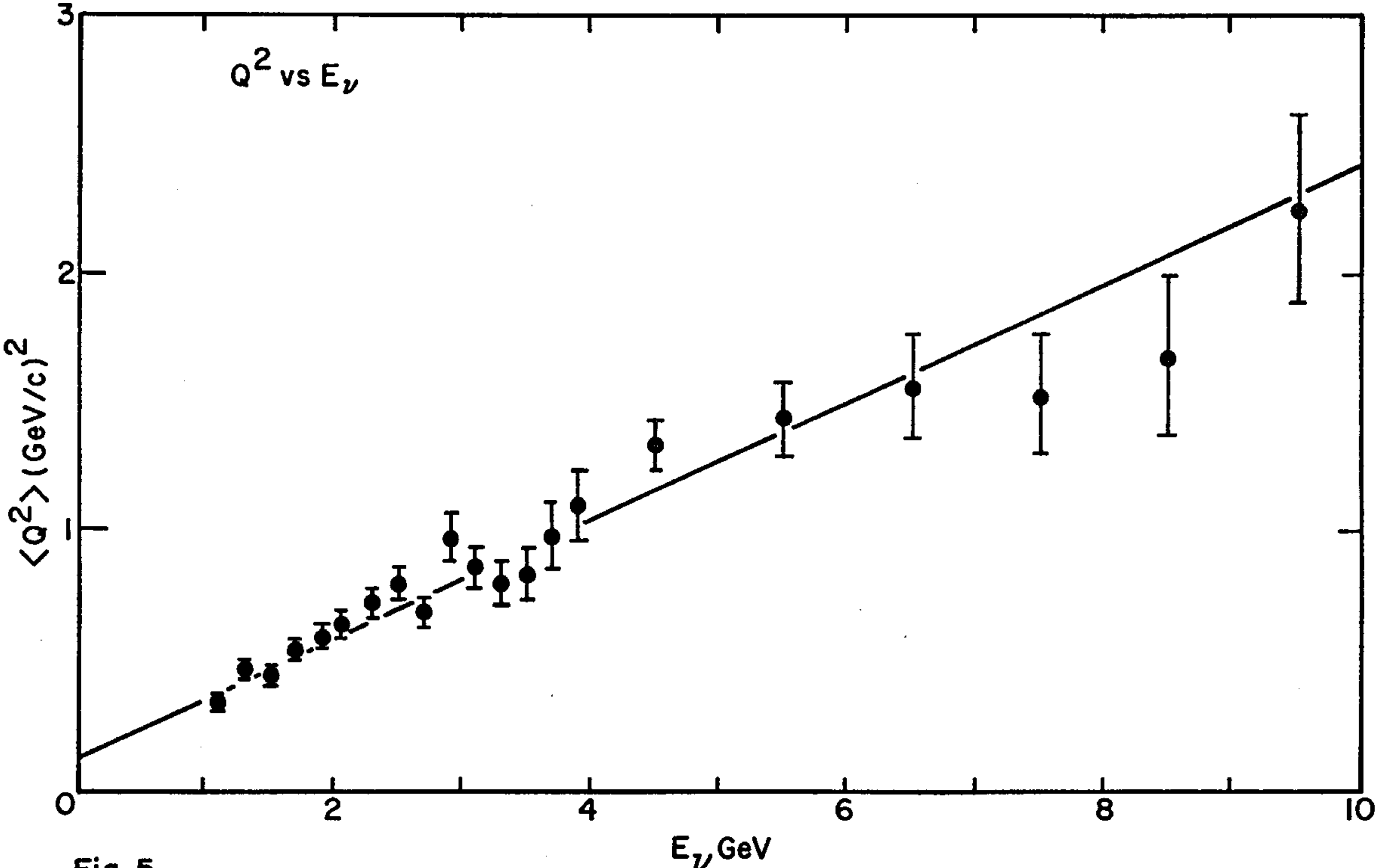

Fig. 5 Mean value of Q^2 as a function of the incident neutrino energy (Ref. 7).

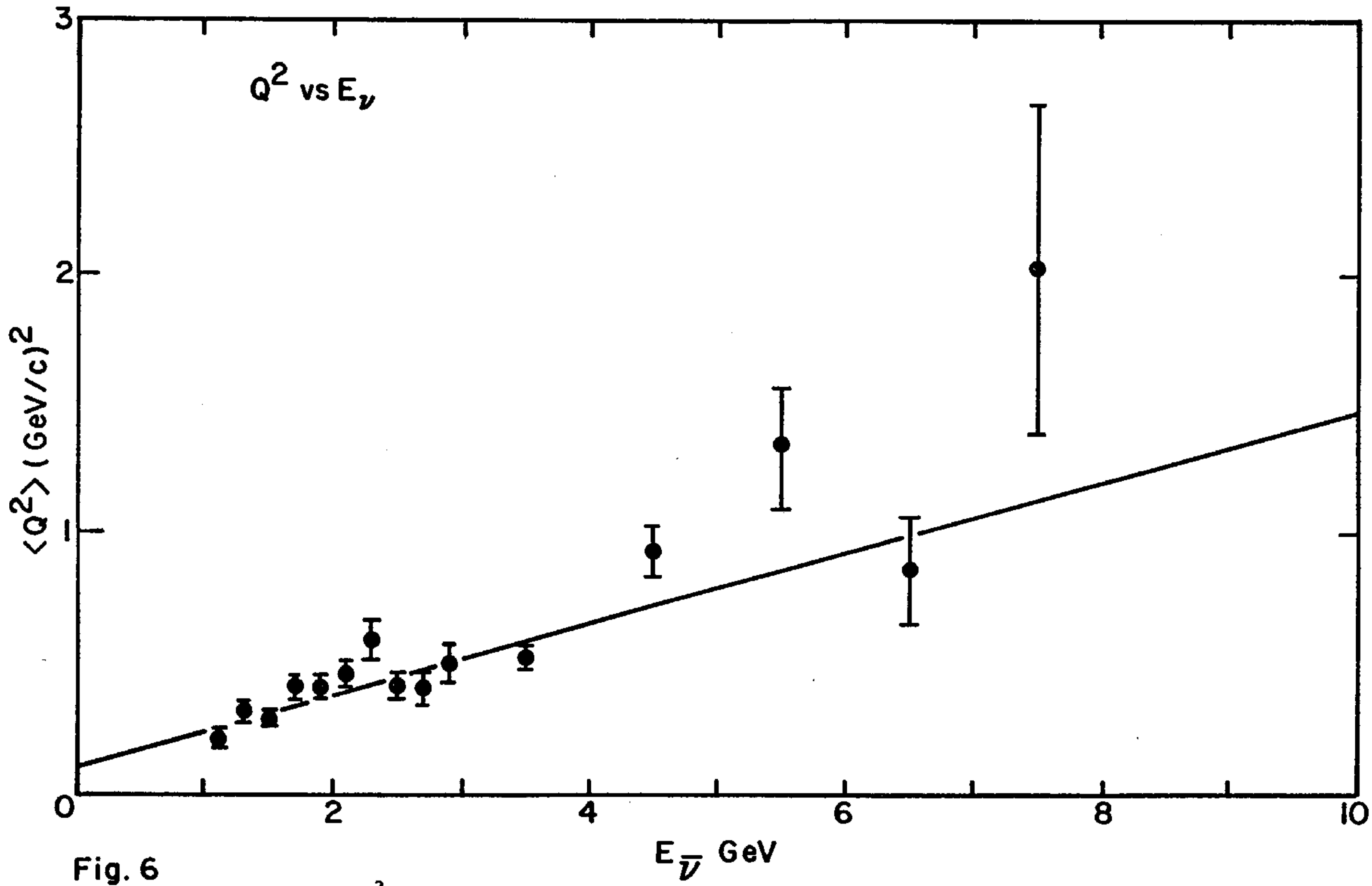

Fig. 6

Mean value of Q^2 as a function of the incident antineutrino energy (Ref. 7).

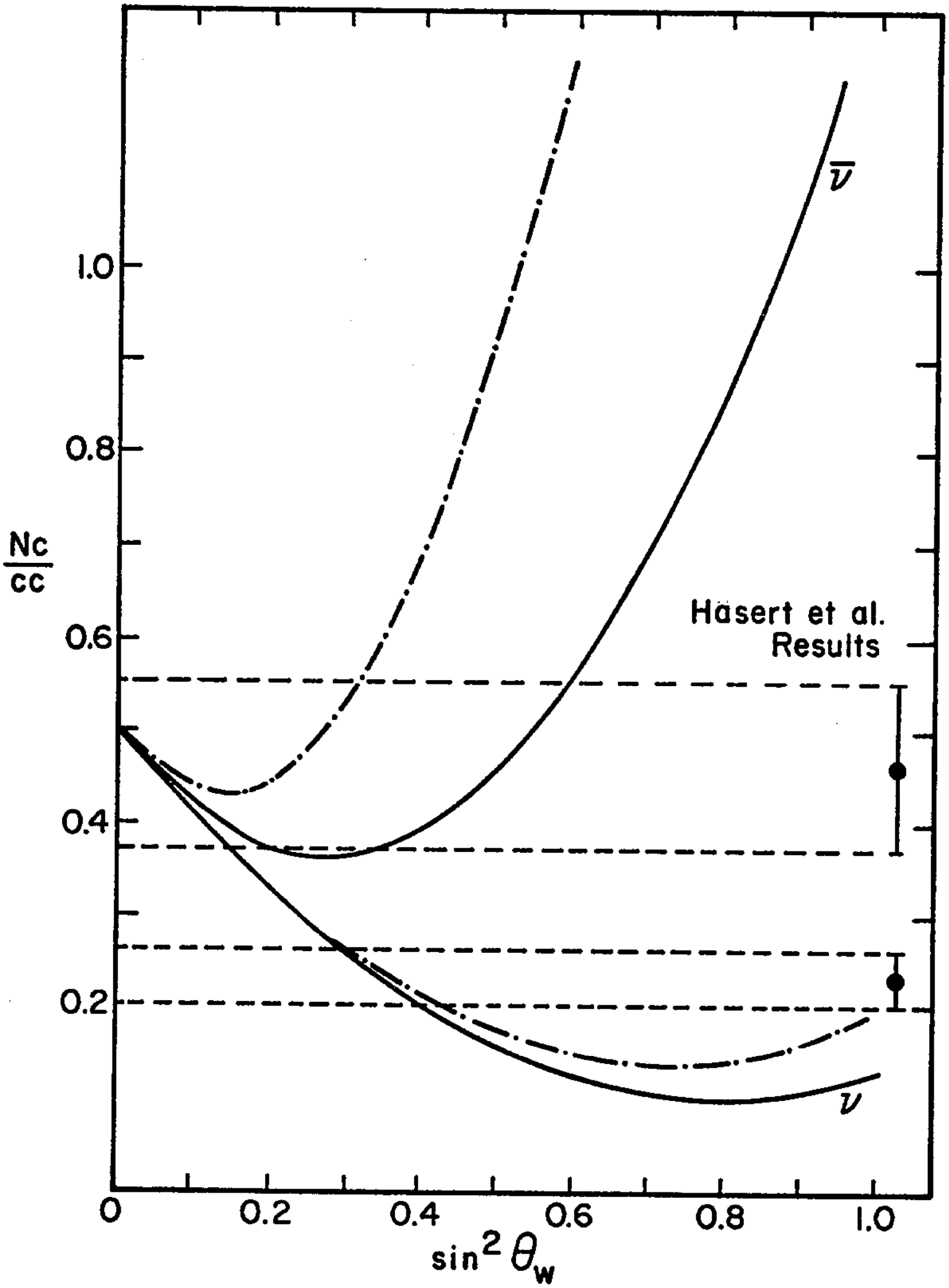

Fig. 7 Lower bounds for the ratio of neutral to charged current contributions. Solid curves are Eqs. (5-15) and (5-16). Dotted curves from Ref. 35.

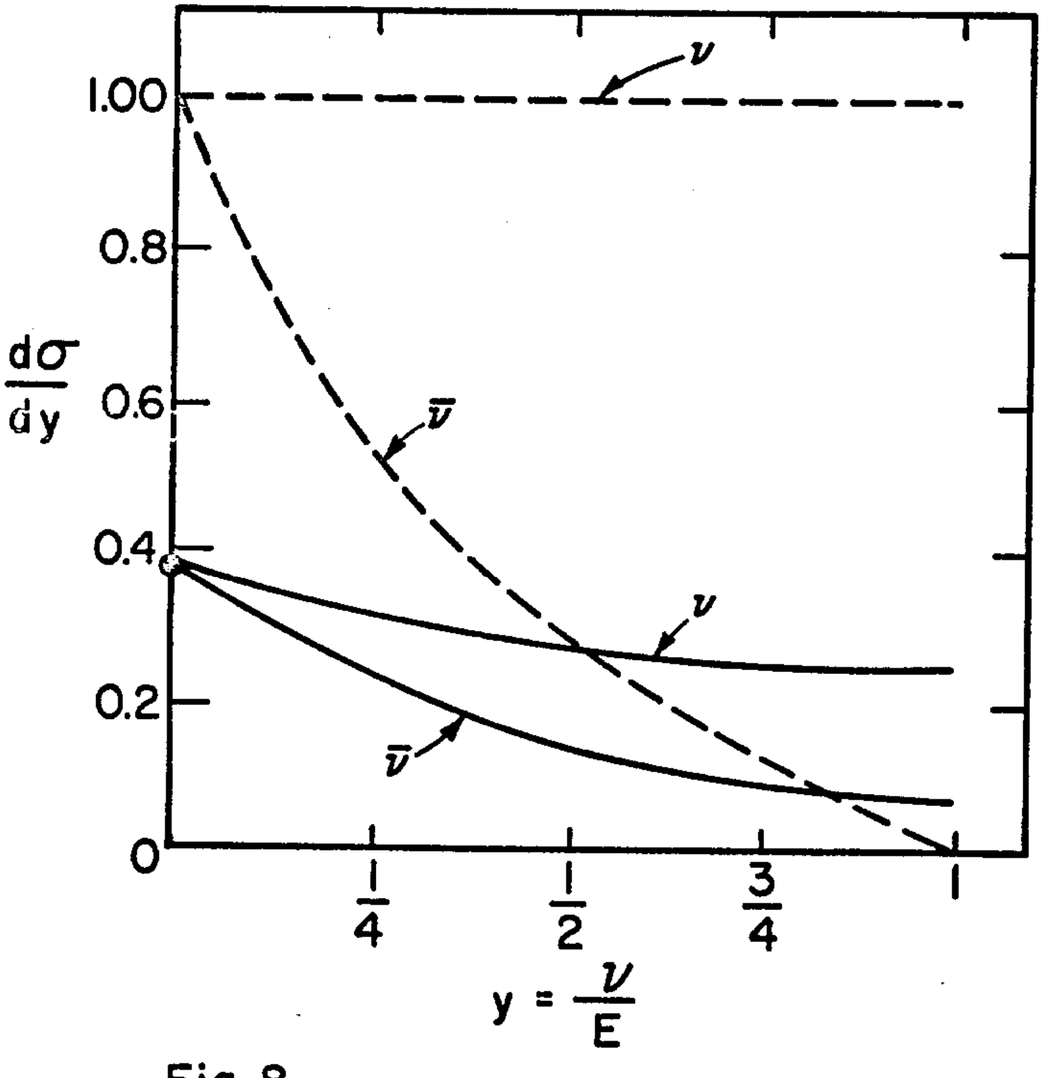

Fig.8 y-distributions for neutral and charged currents in units of $(G^2ME/\pi)\int F_2(x)dx$. Solid curves correspond to neutral currents and are obtained from Sehgal's paper.